Probing Dark Shower Models at Colliders using Long-Lived Particle Searches

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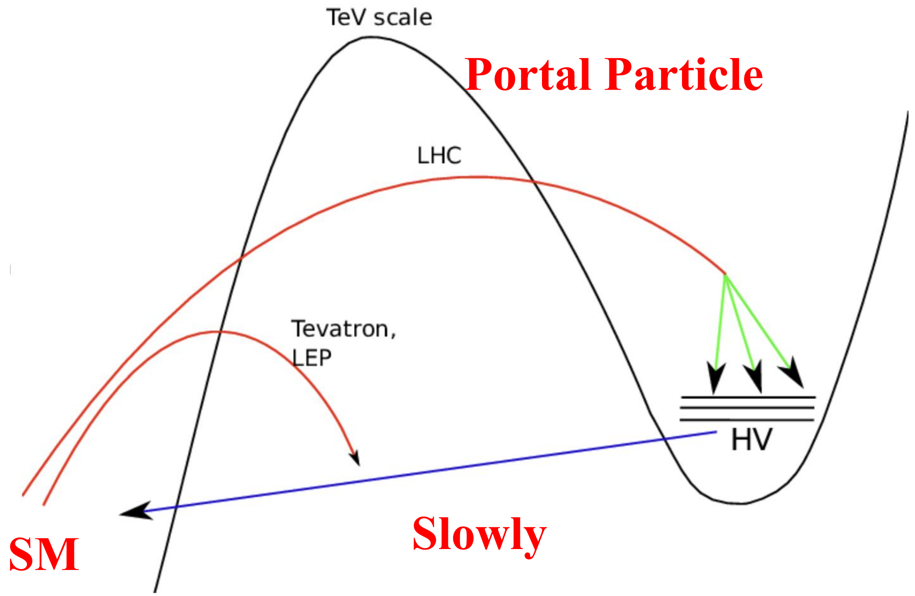
collaboration with Juliana Carrasco, Suchita Kulkarni, Joshua Lockyer, Jose Zurita
Workshop on New Physics Searches at Colliders

Hidden Valley/Dark Sector

- **Hidden Valley** (M. Stassler et al, Phys.Lett.B 651 (2007) 374-379)
  - A Mountain, the heavy portal particles
  - A Valley, dark sector particles, their own interactions
  - decay back to SM particles slowly (LLP)



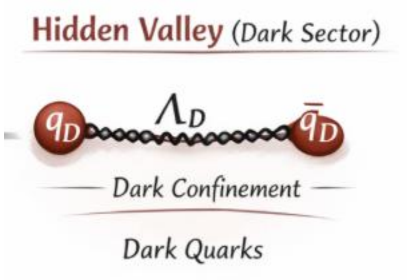
- **Lagrangian**

$$
\begin{aligned}
\mathcal{L} \supset\ & \mathcal{Q}_V^{\mathrm{SM}} \kappa_D Z_D^{\mu} \bar{q} \gamma_\mu q + \mathcal{Q}_A^{\mathrm{SM}} \kappa_D Z_D^{\mu} \bar{q} \gamma_\mu \gamma_5 q \\
& + \mathcal{Q}_V^{D} \kappa_{\mathrm{D}} Z_D^{\mu} \bar{q}_D \gamma_\mu q_D + \mathcal{Q}_A^{D} \kappa_{\mathrm{D}} Z_D^{\mu} \bar{q}_D \gamma_\mu \gamma_5 q_D \\
& + Y_{ij} \phi_D \bar{q}_D q_D + (D_\mu \phi)^\dagger (D^\mu \phi),
\end{aligned}
$$

  - connects the Dark sector and SM with a Z_D portal.
  - Dark QCD sectors

Hidden Valley/Dark Sector

- **Dark Shower**
  - **experimental signals**
  - **dark chiral symmetry breaking scale is low (Valley)**
  - **parton shower and hadronization**
  - **dark quarks form bound states, dark mesons**



- **Free characteristic parameter**
  - Λ_D, **the scale of the Dark QCD**
  - m_{π_D}/Λ_D, **the ratio of dark pion mass to scale**
  - N_F, **the number of flavours**
  - N_C **the number of colors,**
  - $c\tau$ **the proper decay lifetime of long-lived pions**

Hidden Valley/Dark Sector

- **Dark Hadrons** ('snowmass fit', Eur.Phys.J.C 82 (2022) 12, 1132)

$$\frac{m_{\pi_D}}{\Lambda_D} = 5.5\sqrt{\frac{m_{q_D}}{\Lambda_D}}, \qquad \frac{m_{\rho_D}}{\Lambda_D} = \sqrt{5.76 + 1.5\frac{m_{\pi_D}^2}{\Lambda_D^2}}.$$

  - $N_F(N_F$-1) stable $\pi_D^{\pm}$ and N_F π_D^0 as LLP, same for ρ_D

- **Benchmark**

Benchmark name	N_C	N_F/N_C	m_{π_D}/Λ_D	Λ_D GeV	Stable mesons	Meson decay modes
All π_D^0 decay	5	0.5 - 2.5	0.2 - 1.5	0 - 60	All $\pi_D^{\pm}$ 0 π_D^0	$\rho_D^0 \to \pi_D^{\pm}\pi_D^{\pm}$ $\rho_D^{\pm} \to \pi_D^{\pm}\pi_D^0$ $\pi_D^0 \to q\bar{q}$

  - All π_D^0 decay, branching ratio 100% to $q\bar{q}$
  - the decay π_D^0 has lifetime 10 to 1000 mm by hand, as long-lived particle (LLP)
  - $\pi_D^0 \to s\bar{s}, c\bar{c}, b\bar{b},$ according to threshold

Hadronisation Parameters

- **Lund string fragmentation function**
  - **probability for a meson to be produced with momentum fraction z**

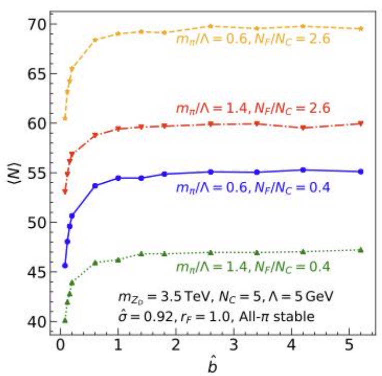
$$f(z) = z^{-1}(1-z)^{a}\exp(-\hat{b}m_T^2/m_Q^2 z).$$

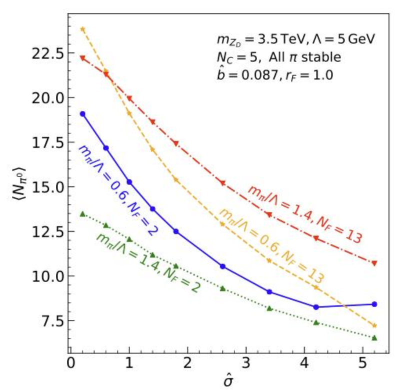
- **Tunneling probability of a $\boldsymbol{q\overline{q}}$ in the WKB approximation**
  - **hadron pT to be given with a variance, $\boldsymbol{\sigma_{PT}/m_Q}$**

$$d\mathcal{P}/dp_T^2 \propto \exp(-\pi p_T^2/\kappa)\exp(-\pi m_Q^2/\kappa).$$

- **SM QCD Default-tune**
  - **HiddenValley:bmqv2 = 0.087**
  - **HiddenValley:aLund = 0.3**
  - **HiddenValley:sigmamqv = 0.92**

- **Dependence of N**





Model Parameter

- **Probvector**

$$\langle N^0_{\pi^0}\rangle = \frac{1-\texttt{probVector}}{N_F}\langle N^0_{\mathrm{tot}}\rangle\,, \qquad \langle N^0_{\pi^\pm}\rangle = (1-\texttt{probVector})\left(1-\frac{1}{N_F}\right)\langle N^0_{\mathrm{tot}}\rangle\,,$$

$$\langle N^0_{\rho^0}\rangle = \frac{\texttt{probVector}}{N_F}\langle N^0_{\mathrm{tot}}\rangle\,, \qquad \langle N^0_{\rho^\pm}\rangle = \texttt{probVector}\left(1-\frac{1}{N_F}\right)\langle N^0_{\mathrm{tot}}\rangle\,.$$

$$\langle N_{\pi^0}\rangle = \left\langle N^0_{\pi^0}\right\rangle + \left\langle N^0_{\rho^\pm}\right\rangle$$

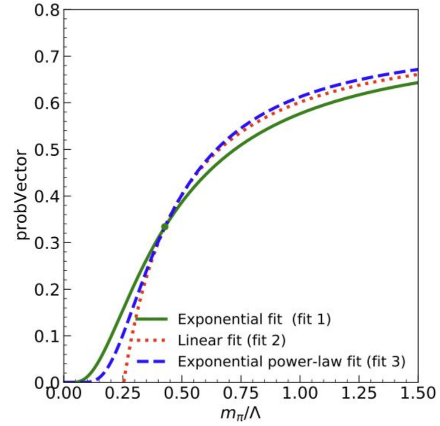
$$\langle N_{\pi^0}\rangle = \left(\frac{1}{N_F} + \texttt{probVector}\left(1-\frac{2}{N_F}\right)\right)\langle N^0_{\mathrm{tot}}\rangle\,,$$

$$\langle N_{\pi^\pm}\rangle = \left(\left(1-\frac{1}{N_F}\right) + \frac{2\,\texttt{probVector}}{N_F}\right)\langle N^0_{\mathrm{tot}}\rangle\,.$$

  - **probvector is the initial ratio of ρ meson to all meson**
  - **$\rho^\pm$meson later decay to $\pi^0 + \pi^\pm$, ρ^0meson later decay to $\pi^\pm$ pairs**

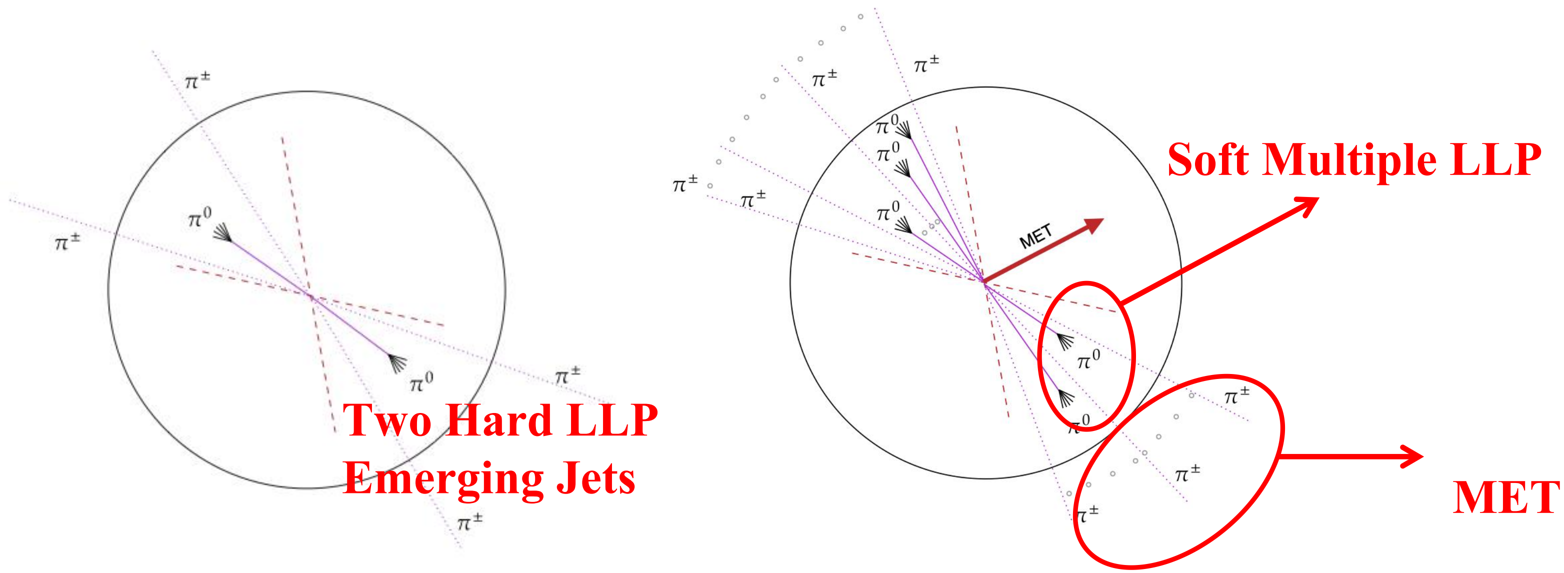
- **Fit from the SM**
  - **probvector=0.33, m_π/Λ=0.428 at SM**
  - **fit with exponential-power-law form**
  - **b=0.59**

$$\texttt{probVector} = \frac{3\exp(1-(m_\rho/m_\pi)^b)}{1+3\exp(1-(m_\rho/m_\pi)^b)};$$



Signal Processes at Colliders

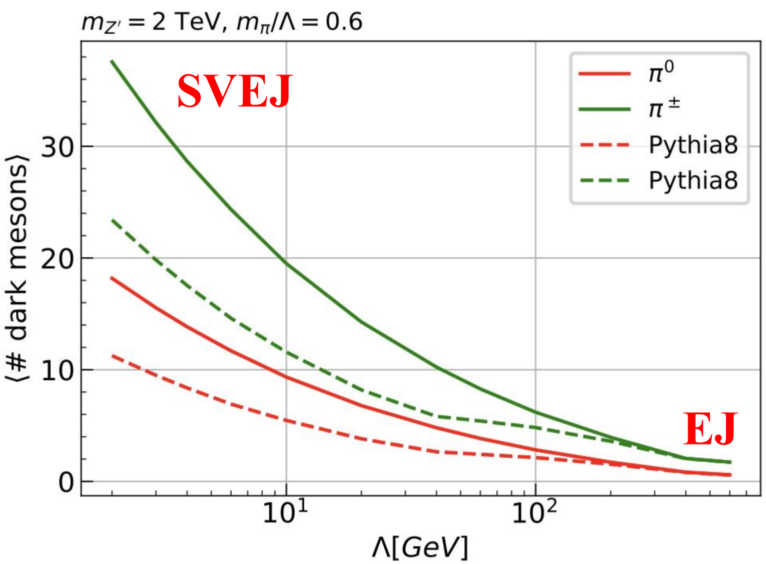
- Semi-visible jets
  - prompt/MET final states (T. Cohen et al, Phys.Rev.Lett. 115 (2015) 17, 171804)
- Emerging jets
  - hard LLP final states, 2→2 process (P. Schwaller et al, JHEP 05 (2015) 059)

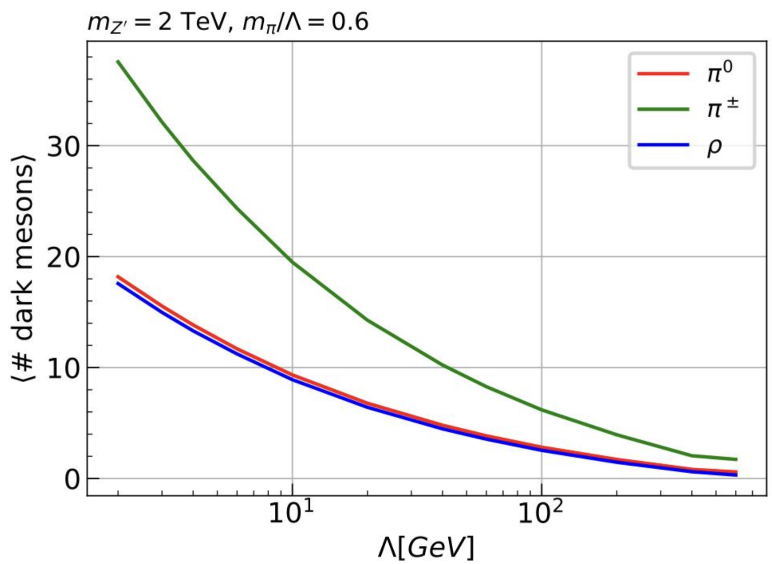


- The semi-visible emerging jets signal
  - pp→ $Z_D \to q_D\overline{q_D}$, with 2 ISR jets, quarks forming hadrons
  - $\pi_D^\pm$ are stable, only part of the jet energy visible, semi-visible jets
  - π_D^0 decays to SM quarks as LLP, emerging jets
  - A novel signal

Semi-visible emerging jets

- **Can we design a new search for semi-visible emerging jets?**
  - **EJ only for large Λ , when we have small N pions, only LLP**
  - **We want small Λ, soft multiple LLPs**
  - **Semi-visible can not probe LLPs**





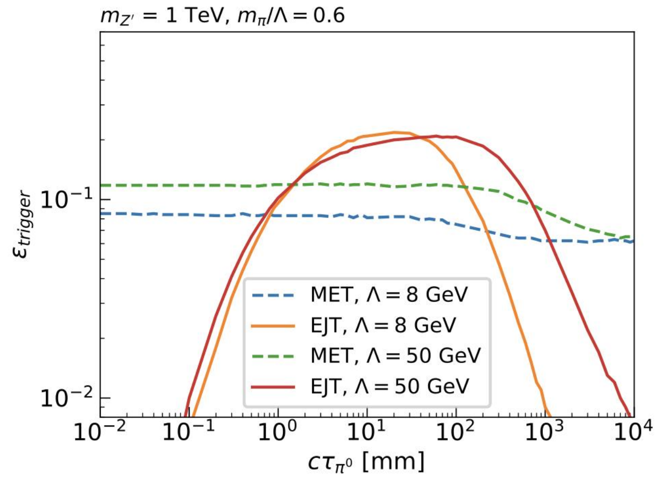
- **How shall we simulate it?**
  - **PYTHIA underestimate number of mesons**
  - **MadGraph + PYTHIA, matched and merging**

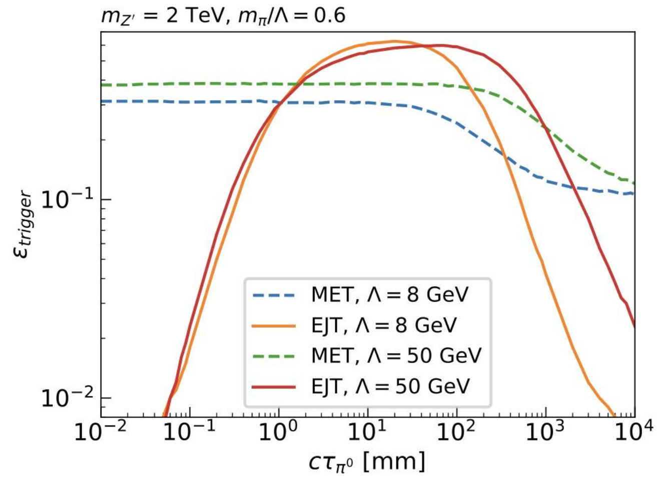
Trigger For SVEJ

- **Existing Triggers**

Trigger efficiencies for $m_{Z'}$ = 1 TeV, $c\tau_{\pi^0}$ = 10 mm			
Trigger	Ref	Λ = 8 GeV	Λ = 50 GeV
MET(> 200 GeV)	[59]	0.0837	0.1227
H_T (> 1050 GeV)	[59]	0.0068	0.0068
MET-H_T (> 100 – 500 GeV)	[59]	0.0615	0.0648
DJ, CMS (H_T > 450 GeV, $n_{DJ} \geq 2$, $n_{pr} \leq 1$)	[61]	0.0656	0.080
DJ-A, ATLAS (p_T > 180 GeV, p_T^{DJ} > 140 GeV, $n_{disp} \geq 3, n_{pr} \leq 1$)	[60]	0.0302	0.0375
DJ-B, ATLAS (p_T > 180 GeV, $p_T^{1,2}$ > 50 GeV, $n_{disp} \geq 3, n_{pr} \leq 2$)	[60]	0.0126	0.0180
EJ ATLAS ($p_T^{R=1}$ > 200 GeV, $\lvert\eta\rvert$ < 1.8, PTF < 0.08)	[60]	0.2062	0.1848

Trigger efficiencies for $m_{Z'}$ = 2 TeV, $c\tau_{\pi^0}$ = 10 mm			
Trigger	Ref	Λ = 8 GeV	Λ = 50 GeV
MET(> 200 GeV)	[59]	0.3150	0.3833
H_T (> 1050 GeV)	[59]	0.0556	0.0568
MET-H_T (> 100 – 500 GeV)	[59]	0.3722	0.3765
DJ, CMS (H_T > 450 GeV, $n_{DJ} \geq 2$, $n_{pr} \leq 1$)	[61]	0.3772	0.4288
DJ-A, ATLAS (p_T > 180 GeV, p_T^{DJ} > 140 GeV, $n_{disp} \geq 3, n_{pr} \leq 1$)	[60]	0.0671	0.1138
DJ-B, ATLAS (p_T > 180 GeV, $p_T^{1,2}$ > 50 GeV, $n_{disp} \geq 3, n_{pr} \leq 2$)	[60]	0.0331	0.0846
EJ ATLAS ($p_T^{R=1}$ > 200 GeV, $\lvert\eta\rvert$ < 1.8, PTF < 0.08)	[60]	0.6084	0.5500





- **EJ is better**
  - **Sensitive to certain decay length, we take $c\tau$ = 10mm**

Selection Cuts

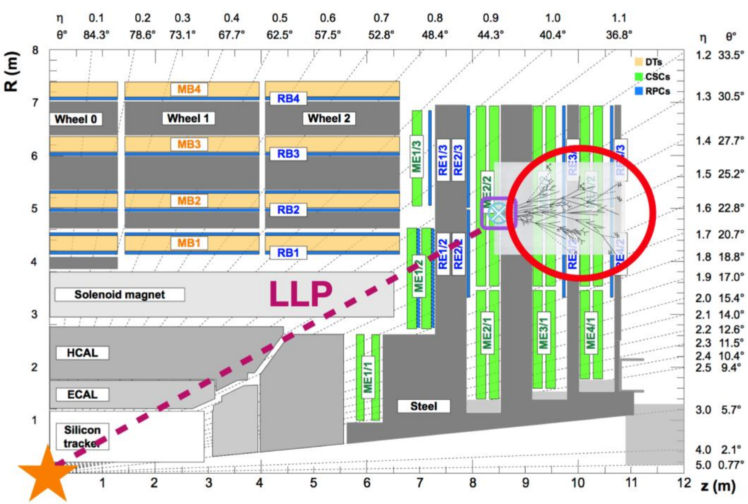
- **Background**
  - **negiligible SM background, we require multiple Displaced vertices (DVs)**
  - **random track crossings, interactions with the material, tracks from cosmic rays, beam halo, etc**

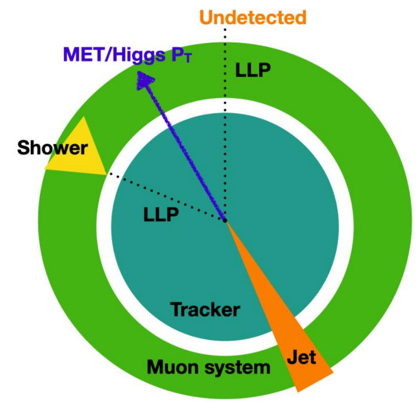
$c\tau_{\pi^0}$ = 10 mm	$m_{Z'}$ = 1 TeV		$m_{Z'}$ = 2 TeV	
Cutflow	Λ = 8 GeV	Λ = 50 GeV	Λ = 8 GeV	Λ = 50 GeV
EJ-trigger	0.2062	0.1848	0.6084	0.5500
$N_{DV} \geq 3$ (≥ 3 trks) in FV	0.1291	0.1172	0.4911	0.4733
1 trk, $\lvert d_0/d_z \rvert < 0.25$	0.1288	0.1159	0.4906	0.4712
1 trk, $\lvert d_0 \rvert >$ 3mm	0.0821	0.0700	0.3619	0.3524
$m_{DV}/\Delta R > 4$ GeV	0.0582	0.0658	0.2906	0.3387
$\Sigma p_T^{DV} > 10$ GeV	0.0527	0.0652	0.2712	0.3366
$d_{vv} > 1/1.5$ mm	0.0526	0.0646	0.2698	0.3322

- **3 DVs, each with 3 tracks**
  - **cut away random track crossing, etc**
  - $\boldsymbol{d_{vv}}$ **make sure they are seperate**
- **1 trk**
  - **cut away pile-up**
- $\boldsymbol{m_{DV}, \sum p_T^{DV}}$
  - make sure a LLP
- No background estimation, though should be small

CMS Displaced Shower Search

- **Displaced Shower search at the CMS muon endcap detector**



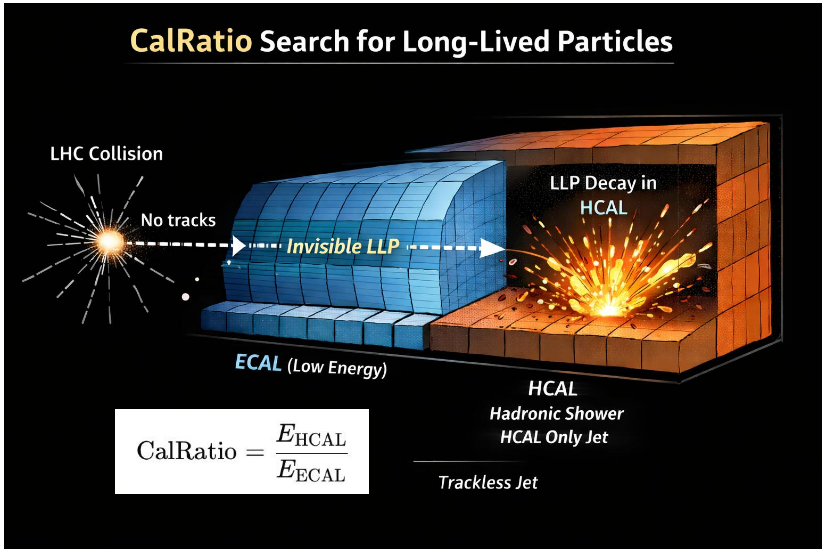


  - CMS collaboration, Phys.Rev.Lett. 127 (2021) 26, 261804
- **Signature**
  - **Energetic LLP, single LLP**
  - **Displaced Shower** at the muon endcap, with $c\tau$~ 1m
  - Number of hits over 130, forming CSC cluster
  - MET > 200 GeV as trigger requirement
  - **Low sensitivity fo soft multiple LLPs**

- **Can we also use it for SVEJ?** **(Phys.Rev.D 112 (2025) 7, 075029)**

CalRatio

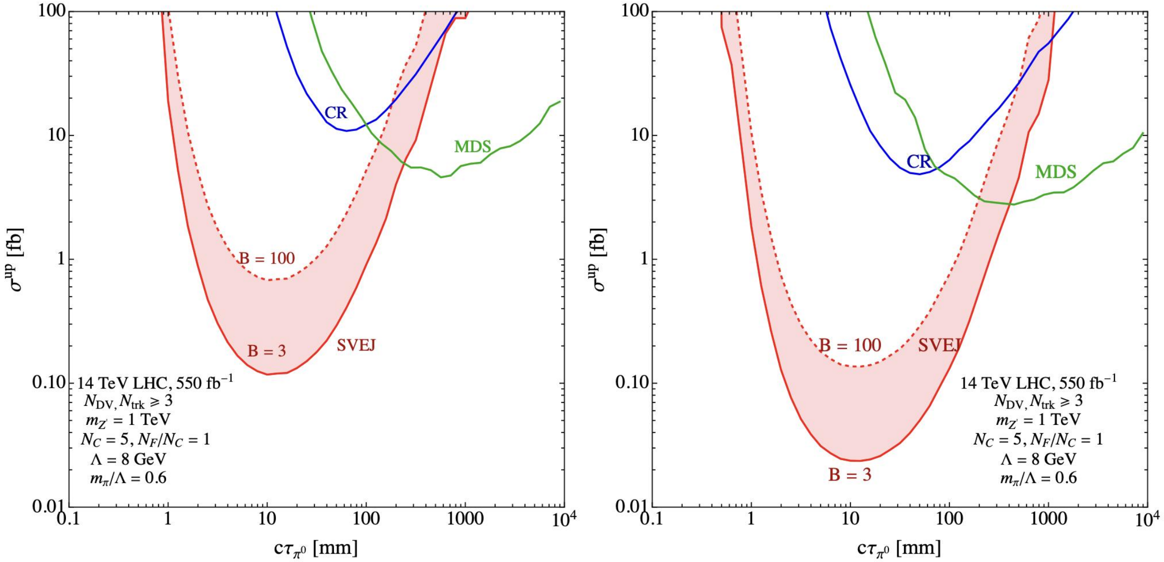
- **High ratio of energies deposited in the HCAL to ECAL**



  - ATLAS collaboration, JHEP 06 (2022) 005
- **Signature**
  - **Energetic LLP, single LLP**
  - **Trackless jet**
  - High HCAL, small ECAL, with $c\tau \sim$ 100mm
- **Re-interpretation material to return efficiency using AI methods**
  - L. D. Corpe et al, Eur.Phys.J.C 85 (2025) 11, 1276
- **Can we also use it for SVEJ?**

Comparison of the three searches

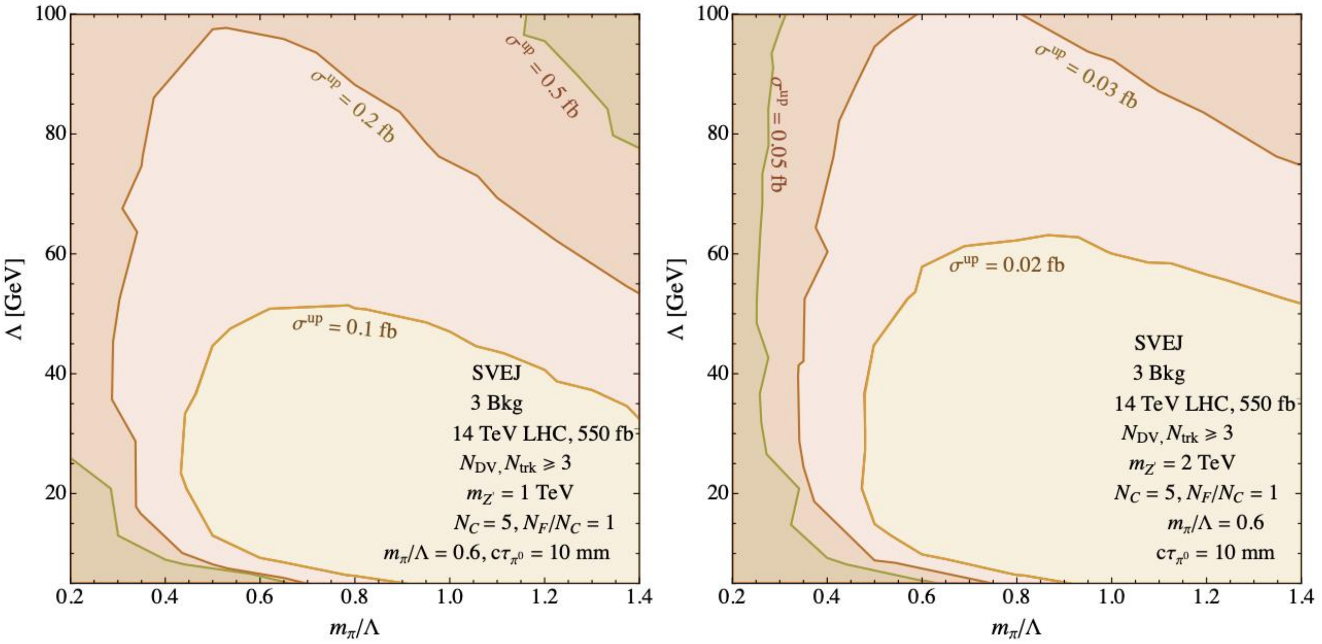
- **Upper limits as a function of $c\tau$**



- **CalRatio**
  - **$c\tau$~ 100mm**
  - **Low sensitivity due to soft multiple LLPs in SVEJ signals**
- **CMS Muon Detector Displaced Shower**
  - **$c\tau$~ 1000mm**
  - **Low sensitivity due to soft multiple LLPs, and low MET in SVEJ signals**
- **SVEJ Search**
  - **$c\tau$~ 10mm, to get tracks**
  - **No background estimation**
  - **Even better when B=10^4 events**

Comparison of the three searches

- **Upper limits as a function of $(\Lambda, m_\pi/\Lambda)$ for SVEJ**



- Favor large m_π/Λ, small Λ
  - Require more pions
  - Require relative heavy DV

- Weak dependence
  - $c\tau \sim$ **10mm is already the sweet point**

Summary

- **HV/DS Model predicts LLPs**
  - **semi-visible jets**
  - **emerging jets**
- **We propose semi-visible emerging jets search**
  - **soft multiple LLPs**
  - **relative small MET**
  - **ATLAS EJ trigger**
  - 3 N_{DV} **, each with > 3 tracks**
  - $c\tau$ **~ 10mm**
- **We compare with General LLP searches**
  - **CMS Muon EndCap Displaced Shower Search**
  - **ATLAS CalRatio Search**
- **Semi-visible emerging jets search is ideal**
  - **low** Λ**,** $c\tau$ **~ 10mm**
  - **Two magnitude better sensitivity due to high efficiency**
  - **Background from algorithm, estimation from experimentists in the future**

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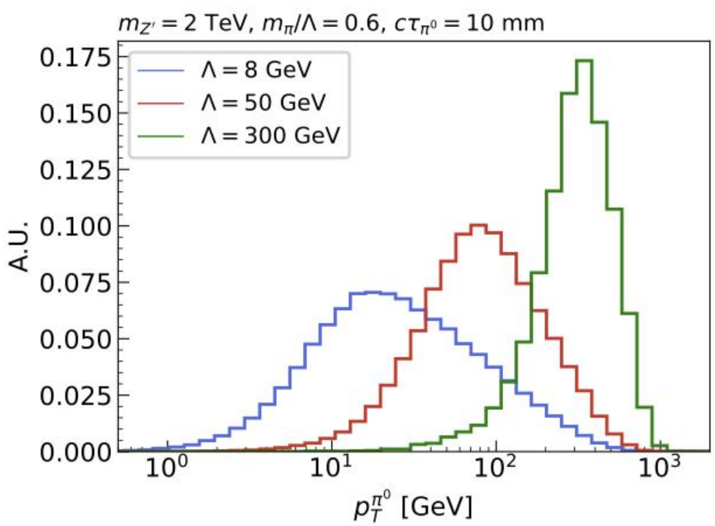
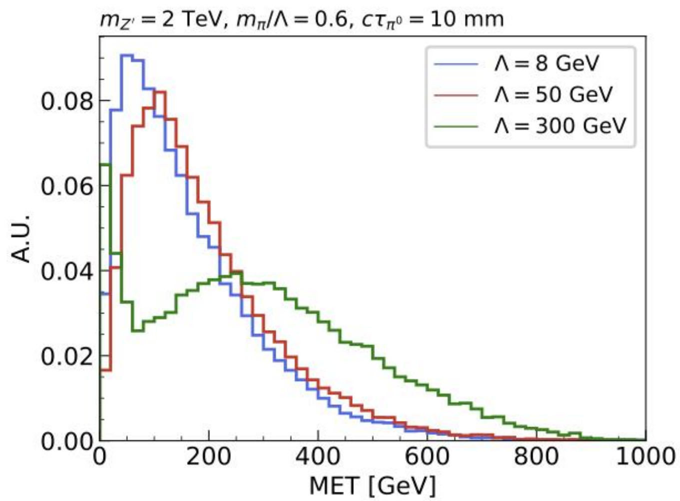
Back Up

Trigger For SVEJ

- **Can we use high pT threshold?**
  - **SVEJ pions are soft**



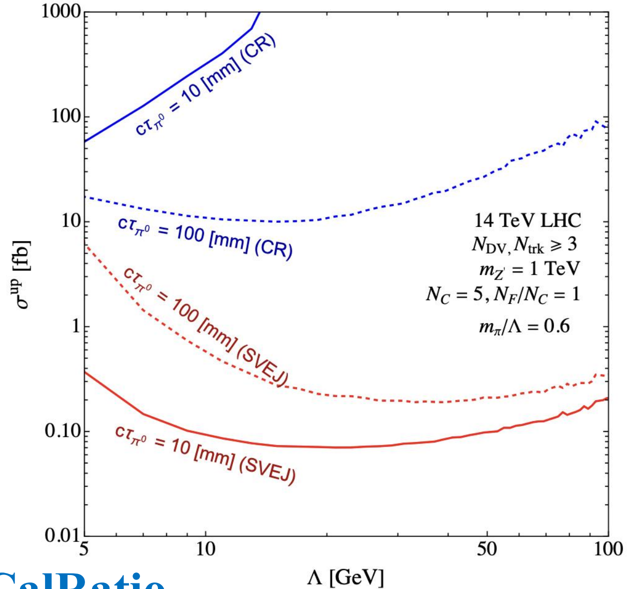


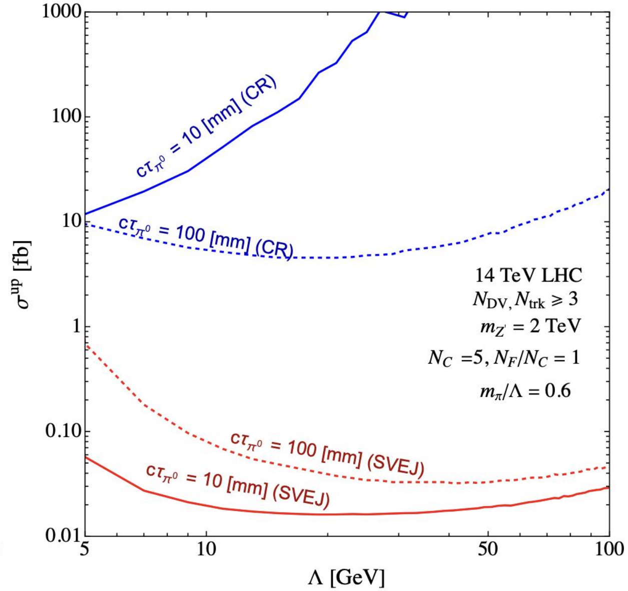
- **Can we use MET?**
  - **Works for EJ**
  - **Falling distribution for low Λ**

- **We can use the existing triggers**

Comparison of the three searches

- **Upper limits as a function of Λ**

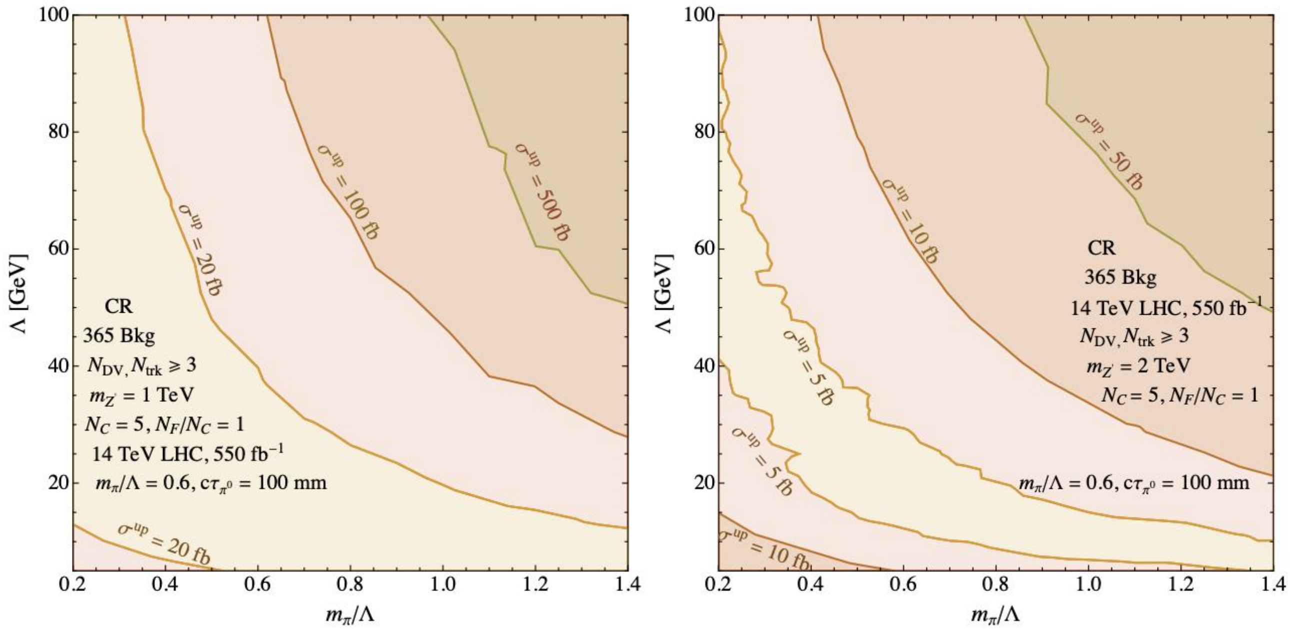




- **CalRatio**
  - **Weak** dependence on Λ, when $c\tau \sim$ 100mm
  - **Strong** dependence on Λ, when $c\tau \sim$ 10mm
- **SVEJ Search**
  - **Strong** dependence on Λ, when $c\tau \sim$ 100mm
  - **Weak** dependence on Λ, when $c\tau \sim$ 10mm
- **Explanation**
  - for fixed m_π/Λ, $\Lambda \uparrow$, $m_\pi \uparrow$, $p/m_\pi \downarrow$, we require $c\tau \uparrow$
  - At the lowest point, moving $c\tau$ lead to small change on σ

Comparison of the three searches

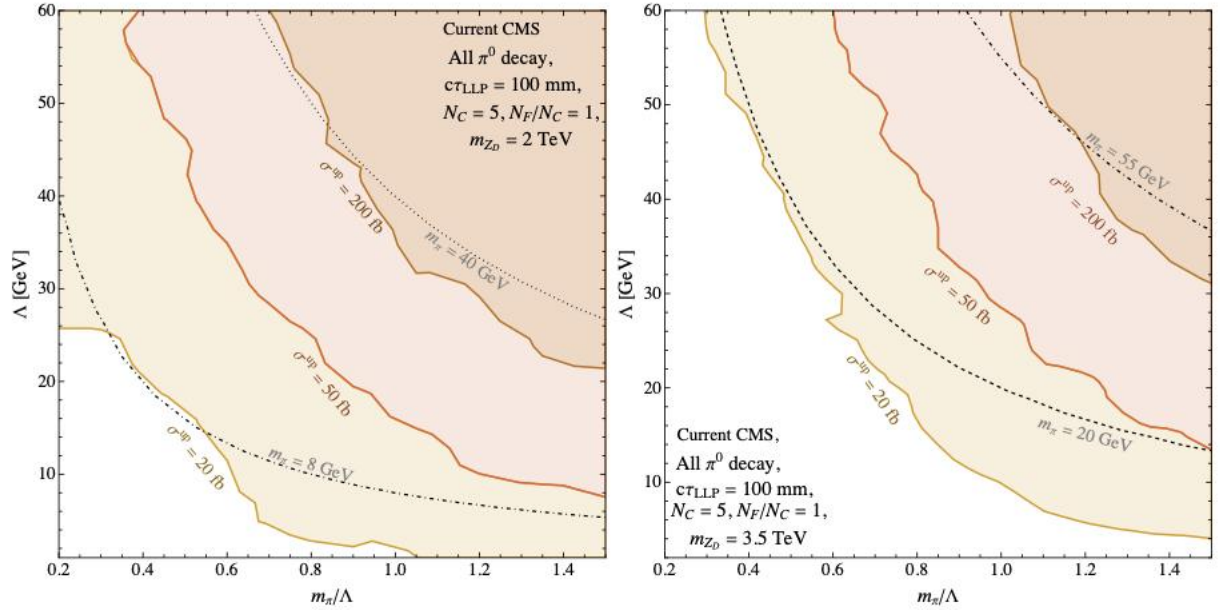
- **Upper limits as a function of $(\Lambda,\ m_\pi/\Lambda)$ for CR**



- **Favor Medium m_π/Λ, Medium Λ**
  - Require $m_\pi \sim 10$ GeV
  - Such boost keep π decay at HCAL
- **Strong dependence**
  - $c\tau \sim$ 100mm is already the sweet point
  - But CR coverage of $c\tau$ is small in log scale

Comparison of the three searches

- Upper limits as a function of $(\Lambda,\ m_{\pi}/\Lambda)$ for CMS Muon Detector



- Favor small m_{π}/Λ, Medium Λ
  - Require $m_{\pi} < 10$ GeV
  - Such boost keep π decay at CMS Muon Detector
- Strong dependence
  - $c\tau$~ 100mm is smaller than the best point
  - require large boost to make π decay at CMS Muon Detector